Towards Reactive Vision-guided Walking on Rough Terrain: an Inverse-dynamics Based Approach

Oscar E. Ramos, Mauricio García, Nicolas Mansard, Olivier Stasse, Jean-Bernard Hayet, Philippe Souères

***Abstract*—This work presents a method to handle walking on rough terrain using inverse dynamics control and information from a stereo vision system. The ideal trajectories for the center of mass and the next position of the feet are given by a pattern generator. Then, an inverse dynamics control scheme relying on a quadratic programming optimization solver is used to let each foot go from its initial to its final position, controlling also the center of mass and the waist. A 3D model reconstruction of the ground is obtained through the robot cameras located on its head as a stereo vision pair. The model allows the system to know the ground structure where the swinging foot is going to step on. Thus, contact points can be handled to adapt the foot position to the ground conditions.**

I. Introduction

Classical walking schemes allow mainly walking on planar homogeneous surfaces. However, there are several works that have succeeded to walk on uneven terrain. These are usually adaptations to a horizontally composed plane or systems where preview control considers information from the current inclination of the upper body. Other methods use predictive attitude compensation control, adjust the ZMP reference to repetitive walking, or use impedance of gains to update the desired landing position. The existing methods do not use visual information to guide the foot on the ground. To consider this type of information, a 3D reconstruction would need to be implemented, but it represents a difficult task in computer vision and robotics. The problem is that depth or range sensors provide a huge amount of data that has to be processed to get high level information, which makes real time reconstruction difficult. One solution is parallel procesing using GPUs that allows to get very efficient 3-D reconstruction systems [1], [2].

This work uses a generic hierarchical optimization solver based on the robot dynamic model to track the position of the CoM and to autonomously control the swinging foot according to the output of a pattern generator. The solver consists of an inverse-dynamics control cascade where motion is represented by tasks. As the foot goes down, possible collisions are detected thanks to the reconstructed map of the terrain which was obtained by the stereo vision system. In this way, collision points are found and handled by the solver, and if necessary, some extremes of the foot are properly taken towards the ground to maximize the support area and without losing dynamic balance.

O. Ramos, N. Mansard, O. Stasse and P. Souères are with LAAS-CNRS, Université de Toulouse, 7 av. Du Colonel Roche, F-31400, Toulouse, France, {oramos,nmansard,ostasse,soueres}@laas.fr.

M. García and J-B Hayet are with CIMAT, A. C., Jalisco S/N Mineral de Valenciana, CP 36240 Guanajuato, Mexico {mjgarciav,jbhayet}@cimat.mx.

II. Description of the methodology

A. Task Function approach

The generation of motion is based on the definition of different tasks whose control laws can be expressed in a subspace of smaller dimension than the full robot state space and then be back-projected to the original space. Such smaller dimension subspace is described by a task function chosen to ease the observation and control of the motion with respect to the task to perform. For the dynamic approach, the task is expressed as a reference behavior for the acceleration.

Some important types of tasks are: proportional derivative (PD) tasks, and interpolation tasks. The former ones specify only the desired position and velocity, and for this case the time to achieve the desired objectives depends on the proportional and derivative gain values. The latter ones add a hard time constraint for the fulfillment of the task [3] and, thus, no gain is required.

B. Control using an inverse dynamics stack of tasks

The control of humanoid robots typically considers several objectives at the same time and not all with the same priority. These objectives can be of two types: equalities (like desired positions or orientations), or inequalities (like joint limits, collision avoidance, or vision field of view). To handle both types of objectives at any level of the priority scheme, a Hierarchical Quadratic Program (HQP) with low computational cost was proposed in [4].

The control using this solver and considering the inverse dynamics model of the robot, the contact constraints (equalities to define the no-motion condition at the kinematic level, and inequalities to define the unidirectionality of contact forces), and different tasks to constraint or generate some useful motion is called the inverse dynamics stack of tasks (SoT) and was proposed in [5]. Tasks can be specified following different criteria, with any priority and in any space, which gives a wide flexibility to this control methodology. A formulation to reduce the computation time for this framework was proposed in [6] as a decoupling between the motion and forces spaces, and is used for this work due to its efficiency.

C. Pattern Generator

The pattern generator proposed in [7], which regulates the speed of the CoM and obtains the foot placement as output of the optimization process is used. The optimization problem in this case is stated as a function of the desired mean value for the speed of the CoM, and the reference for the ZMP. These ZMP references are not fixed in advance but are permanently recomputed from the feet position decided by the algorithm so that the ZMP lies in the middle of the foot.

D. 3-D Reconstruction using stereo vision

A similar approach to the real-time one proposed in [1] has been used. This approach, originally developed for a RGB-D sensor, considers the 3-D surfaces as zero-valued level sets of a function defined over the workspace volume, called the truncated signed distance function (TSDF). The basic steps are: (i) filter the raw measurements from the RGB-D sensor; (ii) integrate the measurements to a volumetric grid using the TSDF; (iii) predict a surface using ray-casting over the zero-crossings of the TSDF; and (iv) estimate the transformation between the measured surface and the predicted one using iterative closest point algorithm (ICP). This approach can be extended to stereo systems. Although the stereo data is noisier than the one from RGB-D sensors, it is a passive sensor and can be used outdoors in sunlight condtions.

To use the stereo system, a disparity map from a pair of rectified images is estimated, and the depth map is derived from it. Several algorithms to estimate disparity maps exist, but since a real time one is needed, the one proposed in [9] has been evaluated. This algorithm estimates a piece-wise disparity map using a sparse disparity map of high textured points as vertices to get subregions of the image, and then esimates the dense disparity map of each subregion using the sparse one as a prior in a probabilistic scheme.

E. Using the pattern generator with visual information and control scheme

The pattern generator gives the desired trajectory of the CoM and the swinging foot assuming a flat horizontal ground. The method proposed here uses the dynamic stack of tasks control scheme with the online output of the pattern generator. While the CoM and the waist are tracked with PD tasks, the swinging foot is not tracked. Since the dynamic solver can handle the notion of contact with a surface (e.g. the rough terrain), only the final position of the swinging foot is considered through an interpolation task that makes the foot go from its initial to its final position. However, depending on the terrain, the real final position might be different from the ideal one calculated in the pattern generator.

The model of the ground obtained with the stereo vision reconstruction allows the system to know where the collision points with the foot will be. The task for the foot is interrupted as soon as a contact appears leading to a possible rotation of the foot to reach stability. In this case, when there is no regular ground, the interpolation will not end but will be interrupted as soon as some point(s) on the foot sole touch(es) some part of the terrain. Different heuristics are applied in the cases when there are one, two or three contact points [3] with the objective of gaining the largest possible foot area with the ground and then, the largest supporting polygon, obtaining more balance. The advantage of the proposed system is the usage of visual information to model the ground and adapt the motion generated by a flat-ground pattern generator to some arbitrary rough terrain.

III. Results

The system has been tested using the dynamic model of the HRP-2 robot. Since structured light RGB-D sensors are not present on the robot, the stereo vision system located in the head of the robot has been used to reconstruct the ground. Fig. 1 shows the robot walking on the rough ground model obtained by visual reconstruction.

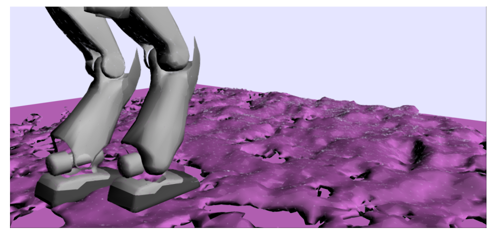

Fig. 1: Robot walking on rough terrain

IV. Conclusions

The control scheme presented in this paper makes the humanoid robot able to walk on rough terrain by detecting collision points with its stereo vision cameras and moving the foot properly to reach a larger support polygon. This approach is grounded on a mathematical reasoning and has been tested in a simulation environment. Even though surfaces might be rough, the method is limited to horizontal cases and would fail if the ground has a large slope, in which case, a modification in the pattern generator would be needed.

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